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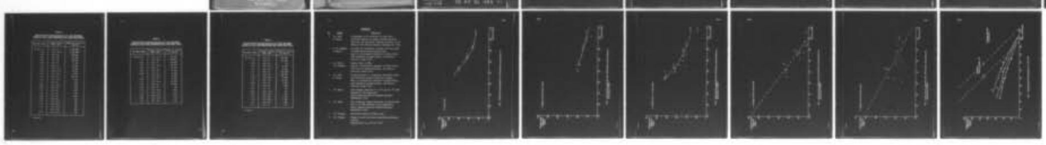

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THE INFLUENCE OF MEAN STRESS ON THE FATIGUE LIFE OF CARBON FIBRE REINFORCED PLASTICS WITH FIBRE ORIENTATIONS OF ±45°

by

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17. Abstract

Tensile fatigue tests have been performed to assess the effect of changes in mean load on the fatigue behaviour of $\pm 45^{\circ}$ orientations of carbon fibre reinforced plastics.

The results have been plotted as a master diagram from which it is clear that it is the value of mean and cyclic stresses and not simply the value of the peak stresses which determines fatigue life.

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THE INFLUENCE OF MEAN STRESS ON THE FATIGUE LIFE OF CARBON FIBRE REINFORCED PLASTICS WITH FIBRE ORIENTATIONS OF ~~±45°~~

Plus or Minus 45 Degrees.

by

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J. B./Sturgeon

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PLUS OR MINUS 45 DEGREES

SUMMARY

Tensile fatigue tests have been performed to assess the effect of changes in mean load on the fatigue behaviour of ±45° orientations of carbon fibre reinforced plastics.

The results have been plotted as a master diagram from which it is clear that it is the value of mean and cyclic stresses and not simply the value of the peak stresses which determines fatigue life.

Departmental Reference: Mat 337

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LIST OF CONTENTS

1 INTRODUCTION

Early fatigue results[1-3] on unidirectional carbon fibre reinforced plastics (CFRP) which contained high modulus type 1 or high strength type 2 fibres all indicated the same sort of behaviour, namely, that axial fatigue failure occur only when the peak, maximum and minimum, stresses approach the tensile or compressive strength of the composite. Unfortunately no comprehensive study has been reported which investigates the effect of mean load on fatigue of unidirectional 0^o CFRP but data are available for cross-plied $0 + 90^o$ composite containing type 1 fibres[4]. These give S-N diagrams which are fairly flat so that small changes in dynamic amplitude cause large changes in endurance. Also, the maximum dynamic amplitudes in through-zero fatigue are very large even at long lifetimes and their magnitude can reach values which are only a little short of the compressive strength. On plotting master diagrams to show the relationship between dynamic amplitude and mean stress at constant life, it is clear that there are three distinct regions. In the first, at mean stresses mid-way between the tensile and compressive strengths, the fatigue life is slightly affected by mean load but the most damaging factor is the dynamic amplitude which remains fairly constant. Whilst the dynamic amplitude is constant peak stresses vary considerably being, of course, roughly linear with mean stress. The second region is where the mean stress is so high that the peak tensile stress can enter the tensile strength scatter band. Here it is the peak stress which dominates. The third region is similar only now it is compressive peak stresses which dominate though, unlike the tensile case, the material does not appear able to sustain stresses which are large enough to enter the compressive strength scatter band, instead they remain just outside.

Recently master diagrams for 0 ± 45^o CFRP have been reported by Bevan[5]. These diagrams are more symmetrical about zero mean stress than Owen's for $0 + 90^o$ material because the compressive and tensile strengths are more nearly equal. They can also be divided into the same three portions as before though there are differences between the two laminate constructions. Firstly, the compressive peak stresses can extend into the monotonic strength scatter band in the same way as the tensile peak stresses enter the tensile strength scatter band but in this material such behaviour only occurs at mean stresses which themselves are quite close to the monotonic strengths. Secondly, the central portion about zero mean stress once again has relatively constant fatigure amplitude but the peak stresses do not approach the tensile and compressive

strengths so nearly as they do in 0 + 90° CFRP, and the dynamic stress amplitude is a smaller proportion of the static strength throughout the whole master diagram.

The materials discussed above carry most load in the 0° fibres which accounts for their good fatigue performance. When no fibres align with the imposed loadings, as in 'off-axis' conditions, both the matrix and the resin/fibre interface are severely loaded and, relative to the monotonic strength, the fatigue performance is not so good as with 0°, 0 + 90° and 0 ± 45° CFRP. This has been shown in axial testing of 90 ± 45° and in 0° and 0 ± 45° material subjected to 3-point bend interlaminar shear loadings[5,6]. In both cases the S-N diagrams are much steeper than for materials containing 0° fibres and relatively large changes in fatigue stresses are required to change the lifetime significantly. Results from axial testing of 90 ± 45° material reveal an asymmetric master diagram, since the compressive strength is twice the tensile strength, and a plateau region in the compressive mean stress segment where the dynamic amplitude is constant indicating once again that the cyclic stresses dominate fatigue behaviour. A similar plateau was also found in the shear tests. In both cases the maximum dynamic amplitude was only one-third of the material strength compared with at least one-half for 0 ± 45° and 0 + 90° composite. These two examples highlight the importance of off-axis and secondary loadings to the fatigue life of a composite structure, whereas with most metallic structures they could well have been ignored. To investigate off-axis secondary loads further a programme has been undertaken to investigate the effect of mean stress and dynamic amplitude on the fatigue endurance of ±45° CFRP subjected to tensile loadings.

2 MATERIALS

High strength low modulus fibres (type 110 SC, 10000 filaments) were used throughout this work. They were supplied pre-impregnated with epoxy resin (Ciba-Geigy MS 1778/$BF_3$400) by Fothergill and Harvey Limited to Specification NM 547 issue 3.

3 LAMINATE MANUFACTURE AND SPECIMEN PREPARATION

A single laminate (SA 124) 1000 × 300 mm was used to provide all the specimens. It was made in the RAE Structures Department autoclave to the following schedule:

(a) Eight layers of prepreg were assembled and placed in the autoclave. A full vacuum of 1 atmosphere was applied inside the bag and the temperature raised to 105°C over an interval of 1.75 hours.

(b) When the temperature had risen to 105°C the controller was reset to 180°C, the vessel pressurised to 830 kPa and the internal bag pressure raised from a vacuum to 170 kPa. About 0.75 hours elapsed before the temperature reached 180°C.

(c) Once a temperature of 180°C had been attained conditions were held stable for 1 hour. The heaters were then switched off and the laminate allowed to cool to 70°C before the pressure was released and the composite removed.

The laminate construction was +45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°.

Plain rectangular specimen blanks were cut from the laminate, their dimensions were: length 110 mm, width 10 mm, thickness approximately 2 mm. End plates of thin aluminium alloy were bonded to each test-piece to prevent damage by the fatigue machine grips. The central unsupported length was 50 mm. A 4mm hole was drilled centrally through the end plates and CFRP beneath so that a pin could be passed through the grips and specimen to prevent slippage during tests at high tensile loads.

4 TESTING TECHNIQUES

Twelve specimens were tested monotonically in a Mayes servohydraulic testing machine type ESH 100D. Load was applied by moving the ram at a constant rate of 2.5 mm/min in position control.

All dynamic fatigue testing was done in an Avery midget fatigue machine type 7306 at a constant speed of 10 Hz.

5 RESULTS

Individual monotonic strength test results are given in Table 1. The average tensile strength was 210.9 MPa with a coefficient of variation of 4.1%.

Table 2 contains individual fatigue test data for a number of preliminary zero-tension tests and these are presented as an S-log N curve in Fig 1. A summary guide to the Tables and Figs containing the tension-tension data are given below:

Mean stress level MPa	Data given in table number	S-log N curve Fig number
75	3	2
103	4	3
125	5	4
150	6	5

In Figs 1 and 3 the dashed line has been drawn by eye. In Figs 2, 4 and 5 the data has been fitted to a straight line using a least squares linear regression analysis. Fig 6 gives the tensile segment of the master diagram based on the data of Figs 1 to 5.

6 DISCUSSION

A number of points stand out in the data of Figs 1 to 5. Each S-N diagram is steep so that large changes in stress amplitude are required, at a given mean stress, to cause a significant change in lifetime. Another point is the increasing scatter in endurance as the mean stress increases, even when the maximum stresses are identical, clearly indicating an influence of mean stress on fatigue. Changes in mean load also affect the dynamic stress amplitude for particular lifetimes as shown in the master diagram, Fig 6. Thus both mean and dynamic amplitudes have a direct influence on fatigue endurance. Indeed there appears to be an almost linear relationship between mean stress and dynamic amplitude within the range of stresses studied. Finally, within this range of stresses there is no evidence of a plateau where the dynamic amplitude is independent of mean stress. At all points on the diagram the mean stress has an influence on fatigue.

The data presented here support Bevan's results of axial fatigue experiments on $90 \pm 45^{\circ}$ CFRP[5] and his results for shear loadings in unidirectional 0° and $0 \pm 45^{\circ}$ laminations containing type 2 fibre in an epoxy matrix[6]. It shows that the curves on the master diagram keep well clear of the static strength scatter band except at very high stresses where normal fatigue testing is almost impossible. It also verifies that when either matrix on resin/fibre interface stresses are high smaller dynamic amplitudes can be tolerated, relative to the monotonic strength, compared with axial tests on 0°, $0 + 90^{\circ}$ and $0 \pm 45^{\circ}$ CFRP. Indeed, by extrapolation, the dynamic stresses at zero-mean load are probably less than $\frac{1}{3}$ of the monotonic strength which is less than Bevan's results for

shear testing[6], showing that ±45° testing is a particularly severe form of test for CFRP. This may be an advantage for material selection procedures since axial tensile tests on material containing 0° fibres are insensitive to changes of resin and environmental conditioning[7] and the ±45° tensile test may be more suitable for screening fibre/resin combinations without recourse to the more severe regime of compression testing and its attendant buckling problems. The low scatter accompanying ±45° tests compared with 0°, 0 + 90° and 0 ± 45° material is a further advantage.

Finally the severity of ±45° loadings is highlighted by comparing the fatigue ratios of a number of composite laminations subjected to zero-tension loadings. The fatigue ratio ${}_{0.0}\mathcal{R}_{10^6}$ has been defined as the ratio of fatigue stress amplitude under zero-tension conditions (stress ratio 0.0) for a life of 10^6 cycles to the monotonic tensile strength[8] and data for 0° and 0 ± 45° CFRP have been taken from earlier work[8].

Fibre orientation	Type of specimen	Fatigue ratio ${}_{0.0}\mathcal{R}_{10^6}$
0°	Plain 8-ply	0.31
0 ± 45°	Plain 6-ply	0.35
0 ± 45°	Plain 8-ply	0.37
± 45°	Plain 8-ply	0.23

7 CONCLUSIONS

(a) In ±45° orientations of CFRP the fatigue life is not determined by the magnitude of the peak tensile stresses alone, instead it depends on both the mean and dynamic stress levels.

(b) Increasing either the mean or dynamic stress whilst maintaining the other constant decreases the lifetime.

(c) Tensile fatigue testing is a severe regime for ±45° CFRP and may be a convenient test for evaluating fibre/resin combinations and their resistance to adverse environments.

Table 1

RESULTS OF MONOTONIC STRENGTH TESTS

Specimen number	Tensile strength MPa
SA 124/ 1	209.9
/ 8	217.7
/ 15	220.1
/ 29	217.6
/ 43	220.0
/ 57	214.5
/ 71	212.3
/ 85	206.9
/ 99	200.2
/113	193.3
/127	201.9
/134	216.1
Average strength	210.9 MPa
Standard deviation (S)	8.65 MPa
Coefficient of variation	4.1%

Table 2

ZERO-TENSION (P ± P) FATIGUE DATA FOR ±45° CFRP SPECIMENS TESTED AT 10 Hz AND ROOM TEMPERATURE

Specimen number	Fatigue stresses MPa ± MPa	Number of cycles to failure
SA 124/ 6	46.7 ± 46.7	3 132 000*
/ 53	48.6 ± 48.6	6 849 000
/ 30	49.4 ± 49.4	1 637 000
/109	50.4 ± 50.4	490 000
/ 16	51.0 ± 51.0	509 000
/132	51.8 ± 51.8	190 000
/ 62	52.2 ± 52.2	203 000
/ 86	53.4 ± 53.4	247 000
/ 39	54.2 ± 54.2	156 000
/ 2	61.8 ± 61.8	30 000
/ 48	63.4 ± 63.4	22 000
/ 25	64.2 ± 64.2	48 000
/118	64.9 ± 64.9	17 000
/ 72	66.2 ± 66.2	30 000
/ 95	67.5 ± 67.5	12 000
/104	79.7 ± 79.7	2 400
/128	80.2 ± 80.2	1 840
/ 81	81.4 ± 81.4	3 170
/ 58	81.8 ± 81.8	3 020
/ 11	83.7 ± 83.7	1 460
/ 34	89.0 ± 89.0	780

* run-out

Table 3

TENSION-TENSION FATIGUE DATA FOR ±45° CFRP SPECIMENS TESTED AT 10 Hz, ROOM TEMPERATURE AND 75MPa MEAN STRESS

Specimen number	Fatigue stresses MPa ± MPa	Number of cycles to failure
SA 124/ 23	75 ± 33.5	1 345 000
/122	75 ± 41.5	1 366 000
/ 98	75 ± 42	664 000
/ 52	75 ± 42.5	4 246 000
/ 75	75 ± 43.5	2 419 000
/ 5	75 ± 45	522 000
/ 28	75 ± 45	1 013 000
/ 80	75 ± 48	171 000
/ 56	75 ± 50.5	246 000
/126	75 ± 50.5	109 000
/ 33	75 ± 51	156 000
/ 10	75 ± 51	85 000
/103	75 ± 52	34 000
/ 93	75 ± 55.5	13 000
/116	75 ± 56	4 000
/139	75 ± 58.5	1 000
/ 46	75 ± 60	8 000
/ 69	75 ± 61	4 000

Table 4

TENSION-TENSION FATIGUE DATA FOR ±45° CFRP SPECIMENS TESTED AT 10 Hz, ROOM TEMPERATURE AND 103MPa MEAN STRESS

Specimen number	Fatigue stresses MPa ± MPa	Number of cycles to failure
SA 124/ 3	103 ± 19	3 984 000*
/ 26	103 ± 33.5	5 585 000*
/110	103 ± 40	229 000
/133	103 ± 42	34 000
/ 87	103 ± 43	322 000
/138	103 ± 43	3 000
/ 91	103 ± 47	26 000
/ 68	103 ± 47.5	52 000
/ 21	103 ± 47.5	91 000
/ 45	103 ± 47.5	10 000
/ 63	103 ± 49	100 000
/ 40	103 ± 55.5	3 000
/ 12	103 ± 63	1 920
/105	103 ± 63.5	1 050
/129	103 ± 64	800
/ 35	103 ± 66	2 250
/ 59	103 ± 67	4 790
/ 82	103 ± 67	2 890
/ 96	103 ± 80	262
/ 49	103 ± 81.5	350
/ 73	103 ± 83.5	920
/ 31	103 ± 83.5	370
/ 7	103 ± 83.5	300
/119	103 ± 84.5	186

* run-out

Table 5

TENSION-TENSION FATIGUE DATA FOR ±45° CFRP SPECIMENS
TESTED AT 10 Hz, ROOM TEMPERATURE AND 125MPa MEAN STRESS

Specimen number	Fatigue stresses MPa ± MPa	Number of cycles to failure
SA 124/ 74	125 ± 31.5	324 000
/ 27	125 ± 32.5	3 778 000
/ 51	125 ± 33	260 000
/ 97	125 ± 34.5	642 000
/121	125 ± 35	59 000
/ 79	125 ± 39	54 000
/102	125 ± 39	15 000
/ 9	125 ± 39.5	65 000
/125	125 ± 41	34 000
/ 55	125 ± 42.5	85 000
/ 32	125 ± 44	94 000
/130	125 ± 52	370
/ 13	125 ± 52.5	1 870
/ 37	125 ± 52.5	1 340
/ 60	125 ± 53.5	5 010
/107	125 ± 53.5	920
/ 83	125 ± 55.5	5 750

Table 6

TENSION-TENSION FATIGUE DATA FOR ±45° CFRP SPECIMENS TESTED AT 10 Hz, ROOM TEMPERATURE AND 150MPa MEAN STRESS

Specimen number	Fatigue stresses MPa ± MPa	Number of cycles to failure
SA 124/ 94	150 ± 24	597 000
/ 24	150 ± 24	103 000
/140	150 ± 24	150
/ 70	150 ± 24.5	10 000
/117	150 ± 26	21 000
/ 47	150 ± 27	923 000*
/ 66	150 ± 28	289 000
/ 89	150 ± 28.5	72 000
/ 19	150 ± 30	61 000
/136	150 ± 30	9 000
/ 42	150 ± 30	5 000
/112	150 ± 32	270
/131	150 ± 37.5	350
/108	150 ± 37.5	340
/ 14	150 ± 38	2 020
/ 38	150 ± 38.5	1 700
/ 61	150 ± 40	1 960
/ 84	150 ± 41	2 400

* run-out

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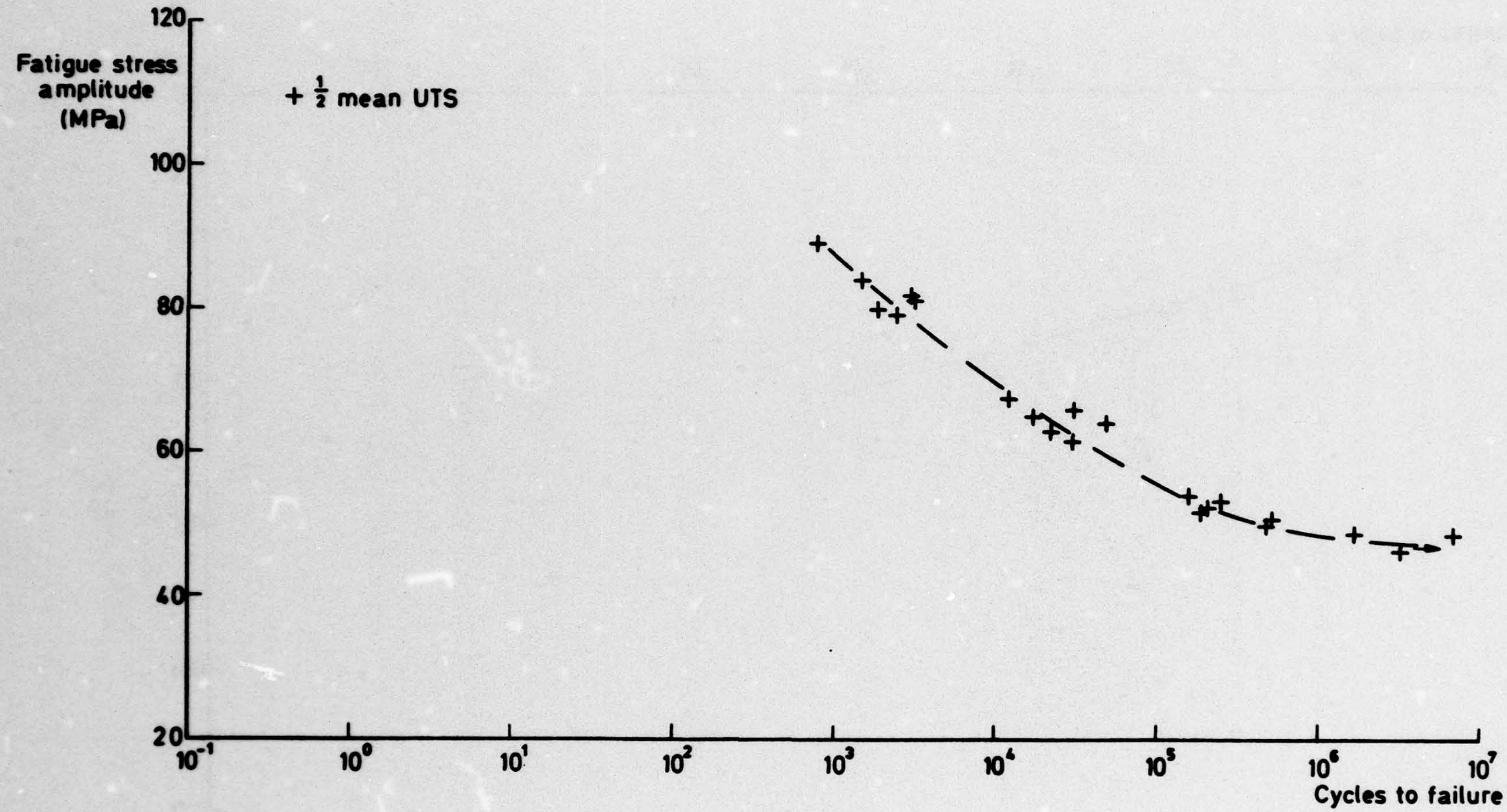

Fig 1 S-log N curve for angle-plied ±45° CFRP tested in zero-tension (P ± P)

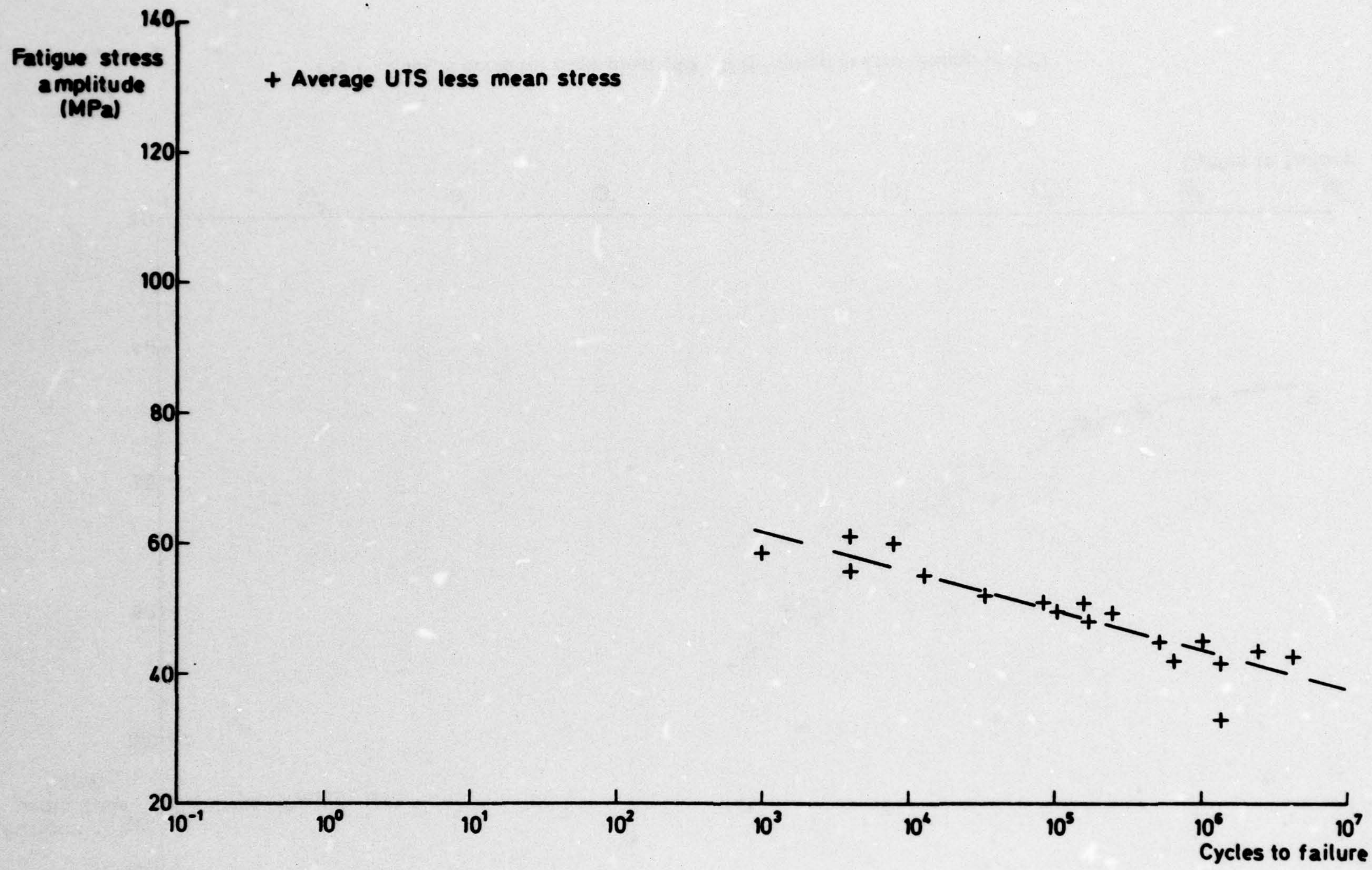

Fig 2 S-log N curve for angle-plied ±45° CFRP tested in tension-tension at a mean stress of 75 MPa

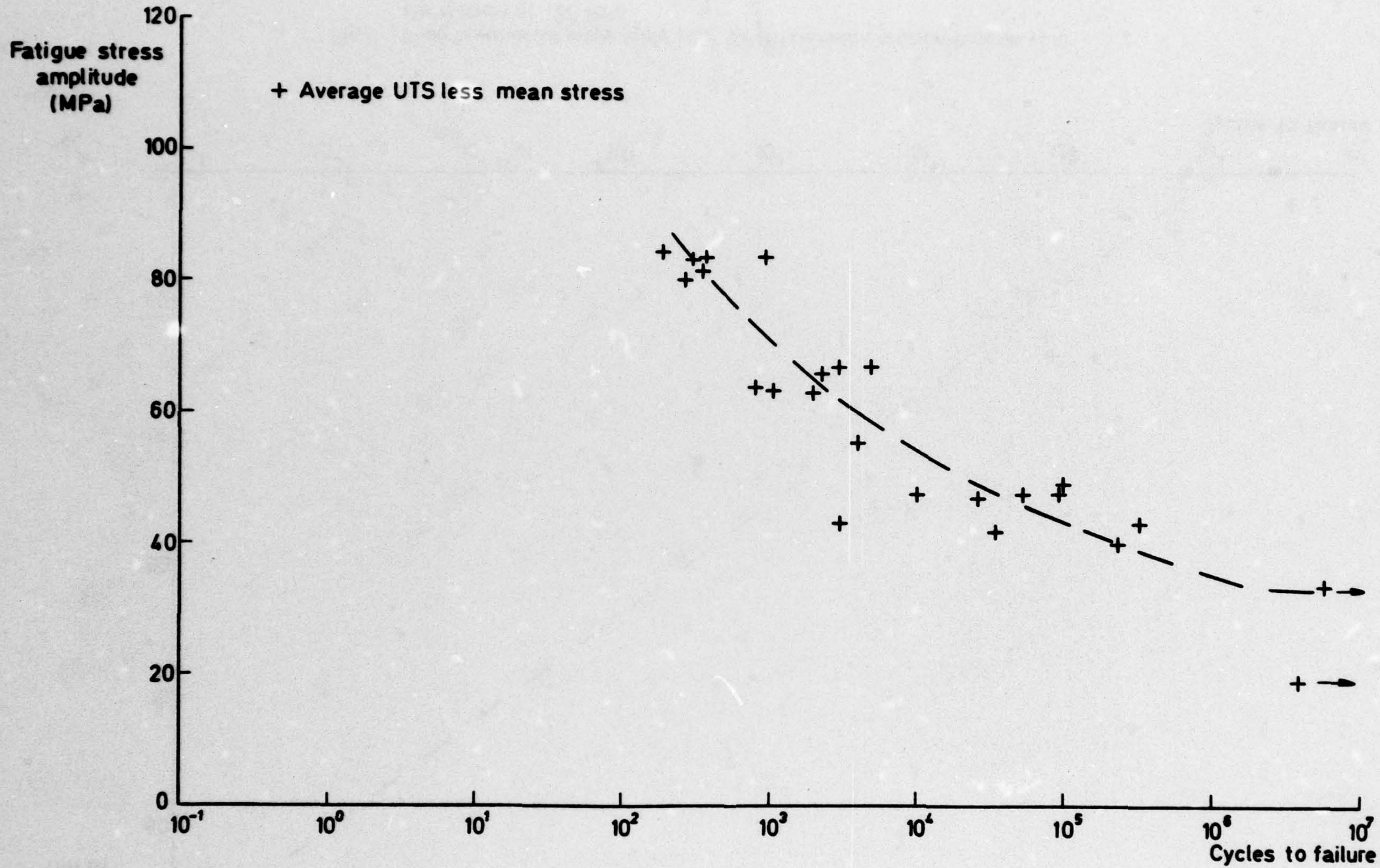

Fig 3 S-log N curve for angle-plied ±45° CFRP tested in tension-tension at a mean stress of 103 MPa

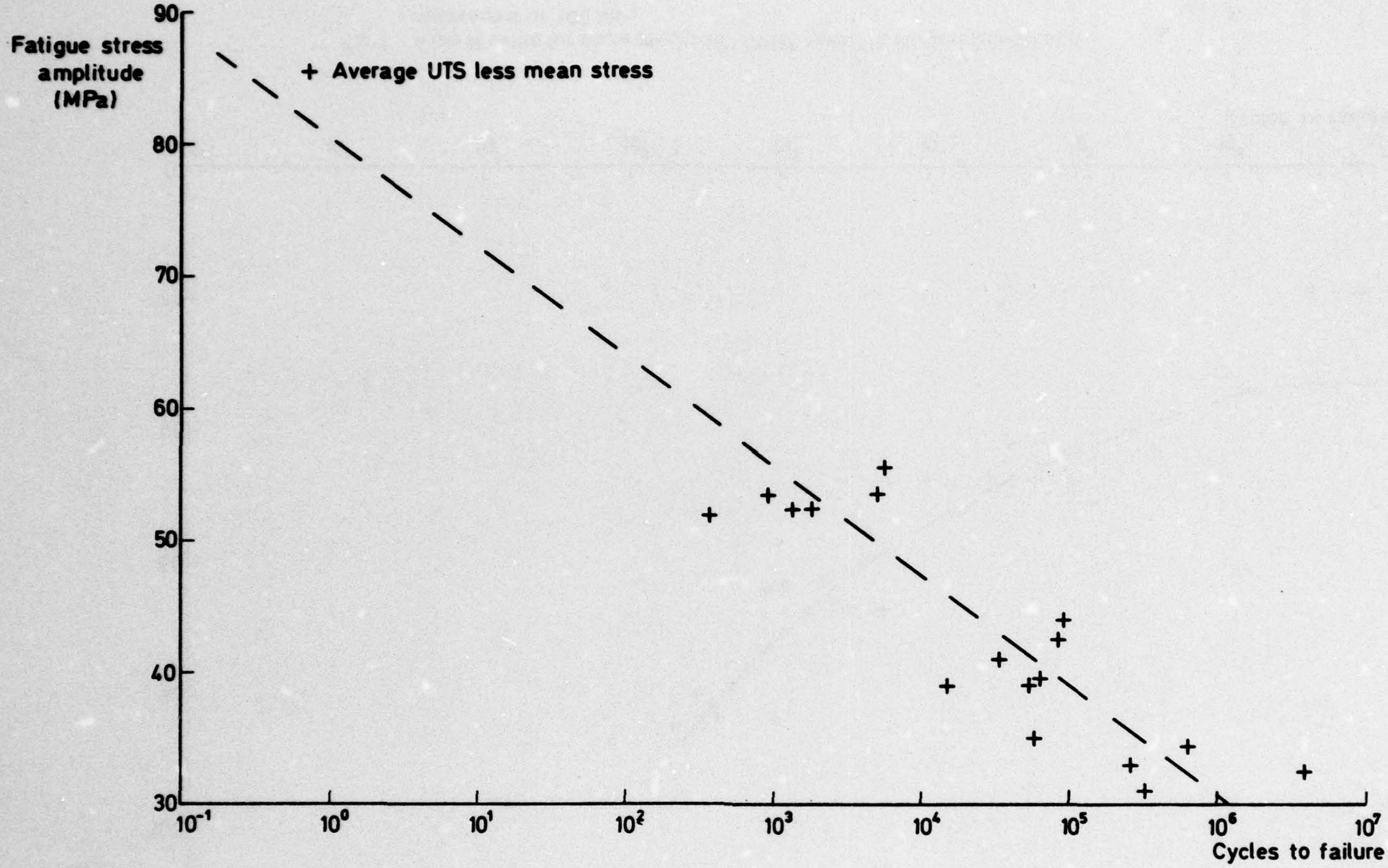

Fig 4 S-log N curve for angle-plied ±45° CFRP tested in tension-tension at a mean stress of 125 MPa

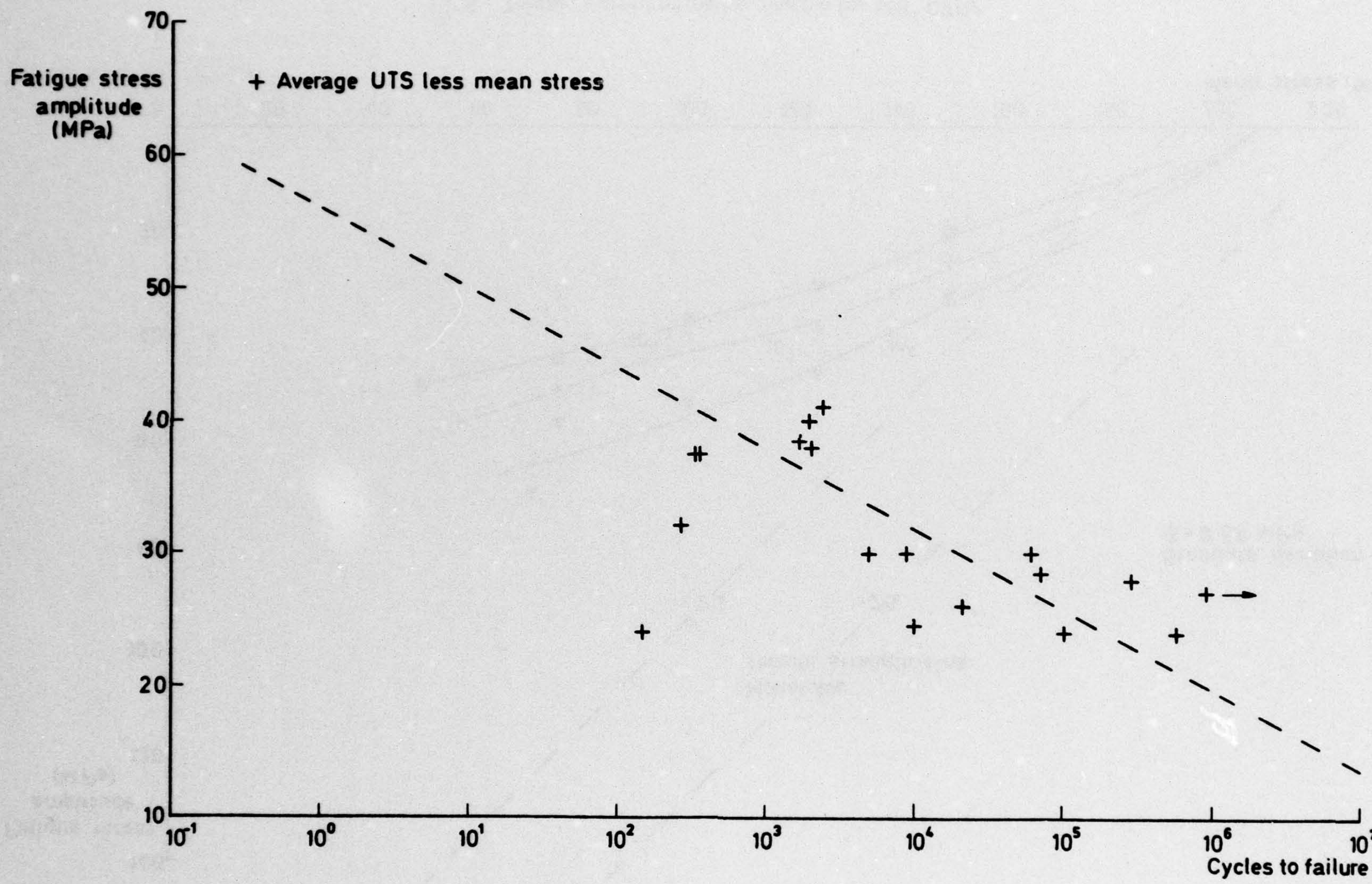

Fig 5 S-log N curve for angle-plied ±45° CFRP tested in tension-tension at a mean stress of 150 MPa

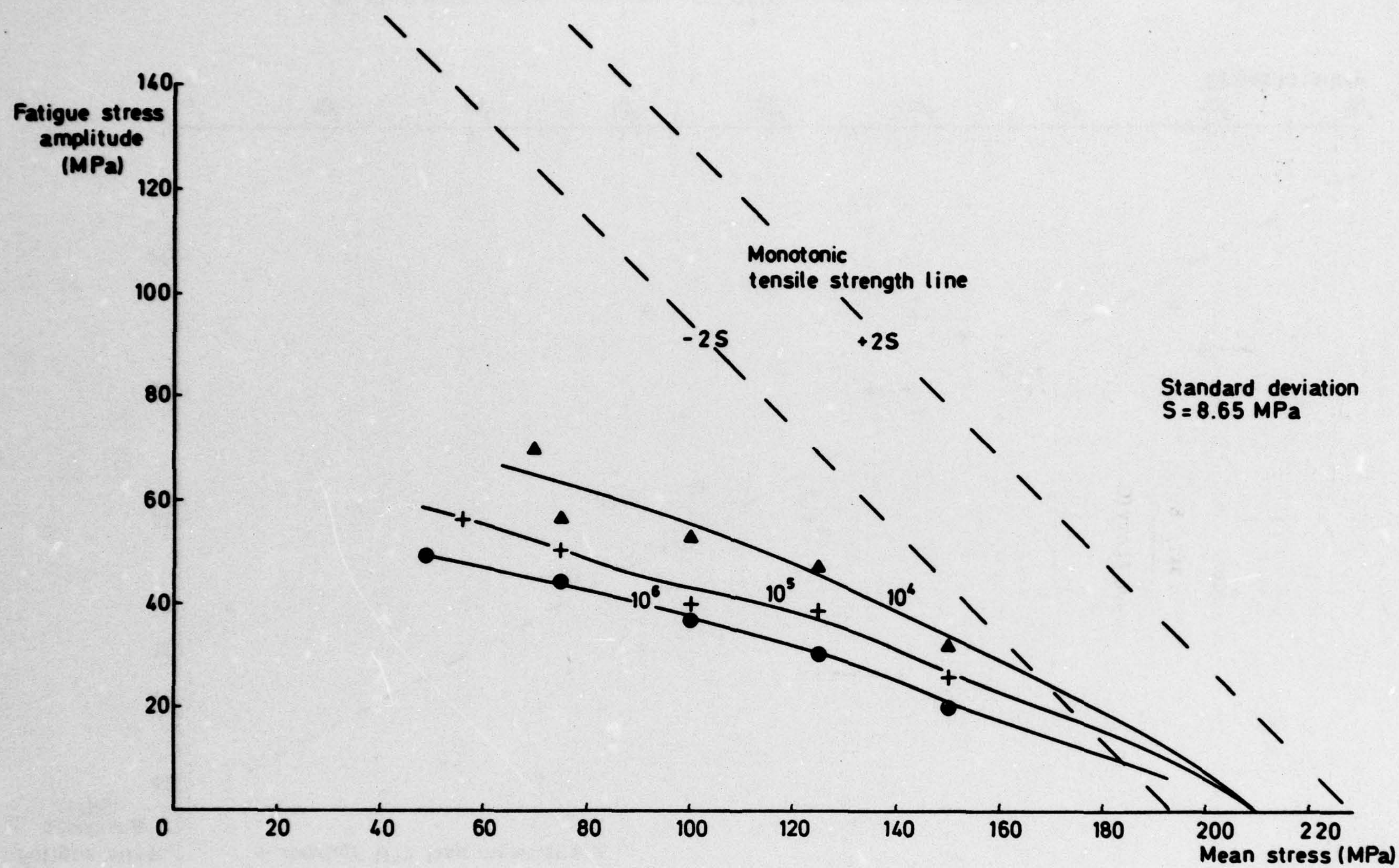

Fig 6 Tensile segment of master diagram for ±45° CFRP